DISCRIMINATION OF EARTHQUAKES AND EXPLOSIONS IN SOUTHERN RUSSIA USING REGIONAL HIGH-FREQUENCY DATA FROM IRIS/JSP CAUCASUS NETWORK

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Abstract

High-frequency regional records from small earthquakes (magnitude < 4.5), and comparable magnitude chemical explosions, are analyzed to find a reliable seismic discriminant in the Northern Caucasus region in Southern Russia. About 130 digital, vertical-component seismograms recorded during 1992 by the IRIS/JSP North Caucasus Network operated by Lamont-Doherty Earth Observatory since 1991 in the distance ranges 10 to 250 km are used. Mean *Pg/Lg* spectral ratios in the high frequency band 10 – 20 Hz are about 1 and 3 for earthquakes and explosions, respectively, in the Northern Caucasus region, Southern Russia. These ratios are much higher than those observed in tectonically stable eastern U. S. where Kim et al. (1993) reported the mean *Pg/Lg* ratios of 0.5 and 1.25 for earthquakes and explosions, respectively in the similar high frequency band.

We find that the high-frequency *Pg/Lg* spectral amplitude ratio in the frequency band 10 – 20 Hz is an adequate discriminant for classifying these events. A linear discriminant function analysis indicates that the *Pg/Lg* spectral amplitude ratio method provides discrimination power with a total misclassification probability of about 7%. The *Pg/Lg* spectral amplitude ratio method we used is sufficiently reliable and robust that it can be used in discriminating chemical explosions (especially numerous mining and quarry blasts) from small regional earthquakes in the routine analysis of regional earthquake monitoring networks.

We are evaluating the *P/Lg* spectral ratio and other potential discriminants using three component regional records. A key to our use of three component regional records for discrimination analysis is correction of the free surface interaction, which allows direct comparison between the *P*-, *SV*- and *SH*-wave amplitudes and reveals clear radiation characteristics from the source.

Keywords: regional crustal waves, seismic discrimination, Caucasus region

OBJECTIVE

Main objective of this research is to improve our knowledge of seismic sources and structure in central Asia including Iran, Caspian Sea and Caucasus Mountains, by analyzing regional high-frequency signals recorded at North Caucasus Network and other regional networks.

Our goals are; 1) to characterize seismic sources in the region and to evaluate reliable seismic discriminants, 2) to determine attenuation of regional phases and to map propagation efficiencies of regional phases along various paths, 3) to determine crust and uppermost mantle velocity structure beneath the Caucasus Network and to locate accurately small events in the region.

Results of our work assist in the monitoring of small seismic events at regional distances for CTBT monitoring.

RESEARCH ACCOMPLISHED

The discrimination of small earthquakes from large chemical explosions (from mines and quarries) based on seismic signals recorded at regional distances (10 – 1000 km) is an important issue facing numerous regional seismic networks. The seismic discrimination problem becomes especially severe in an area with poorly known seismicity such as the southern Russia (Fig. 1). It would be extremely useful to have a reliable and robust criterion that could be used to discriminate earthquakes from explosions in the context of global seismic monitoring.

Most of the previous work on seismic discrimination has focused on separating large underground nuclear explosions from earthquakes in the context of a future comprehensive test ban (e.g., Pomeroy et al., 1982; Evernden et al., 1986; Taylor et al., 1989). In most earlier studies, data available for discrimination analyses were limited to frequencies below 10 Hz, and previous work on regional signals from earthquakes and explosions in the western U. S. suggested that *P* and *S* waves from earthquakes have higher frequency content than signals from explosions (e.g., Murphy & Bennett, 1982; Bennett & Murphy, 1986; Taylor et al., 1988; Chael, 1988). Kim et al. (1993) reported that the mean *Pg/Lg* spectral ratios in the band 1 – 25 Hz are about 0.5 and 1.25 for earthquakes and explosions, respectively, in the eastern U. S. ($\Delta \approx 10$ - 610 km). Further, they found that the high-frequency *Pg/Lg* spectral amplitude ratio in the frequency band 5 – 25 Hz was an adequate discriminant for classifying these events. In the eastern U. S., the *Pg/Lg* spectral amplitude ratio method provides discrimination power with a total misclassification probability of about 1% (Kim et al., 1993).

In the following sections, we report the results of our evaluation of *Pg/Lg* spectral ratio discriminant for the regional earthquakes and explosions in Northern Caucasus region, Southern Russia using digital seismograms recorded at IRIS/JSP North Caucasus Network (Fig. 1).

Characteristics of Regional Seismograms in Southern Russia

A typical vertical-component seismograms from a small earthquake are plotted in a group velocity section in Figure 2. The first *P* and *S* onset arrives with group velocities of about 5.8 km/s and 3.2 km/s, respectively at a distance of about 60 km. This indicates very low *P*- and *S*-wave speeds in the region around the North Caucasus Network. Further, strong *S* to *P* converted phases (*Sp*) observed at stations KUB and MIC suggest the presence of a relatively thick sedimentary layer beneath these stations (see Fig. 2).

Frequency content of regional seismic signals from an earthquake and a quarry blast is

examined using spectrograms (frequency-time display; Fig. 3). Both events are at a comparable distance ranges from KIV ($\Delta \approx 65$ km). The earthquake record is characterized by a strong S wave amplitude at low frequencies (below about 7 Hz), and P and S waves with comparable amplitude at higher frequencies (10-15 Hz). The spectrogram of the quarry blast record shows predominant P wave energy over a wide frequency band 3 - 20 Hz and a weak S waves in this band (Fig. 3). The spectrogram of the earthquake record shows random distribution of seismic wave energy, while the spectrogram of the ripple-fired quarry blast record shows clear spectral banding due to source multiplicity. Time series of these events also show clear differences between the earthquake and explosion records (Fig. 3).

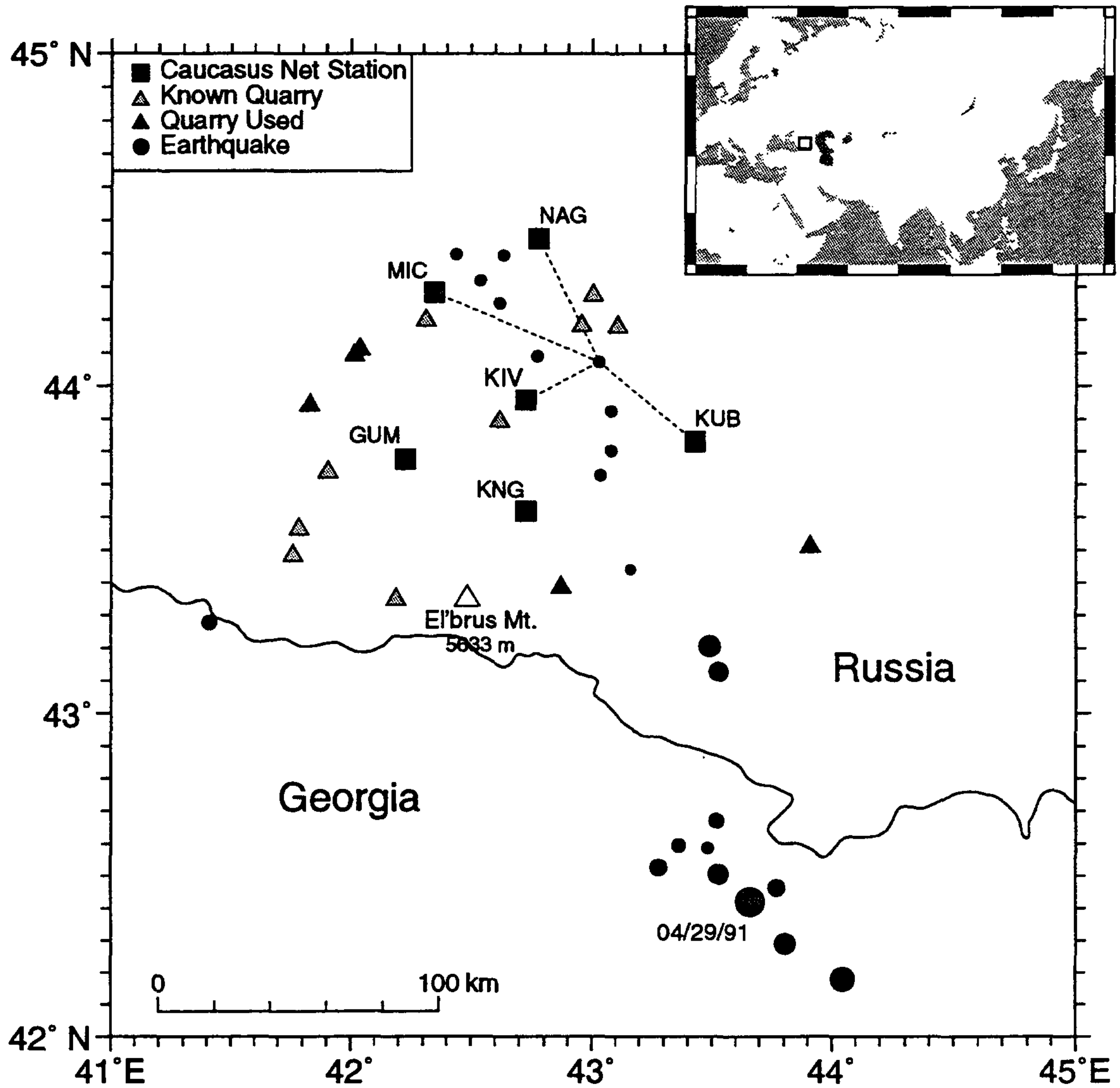

Fig. 1. Locations of earthquakes (*solid circles*), mines and quarries identified and used in this study (*solid triangles*), other known quarries (*open triangles*) and Caucasus Network stations (*shaded squares*). Circle size is proportional to the magnitude of the earthquakes.

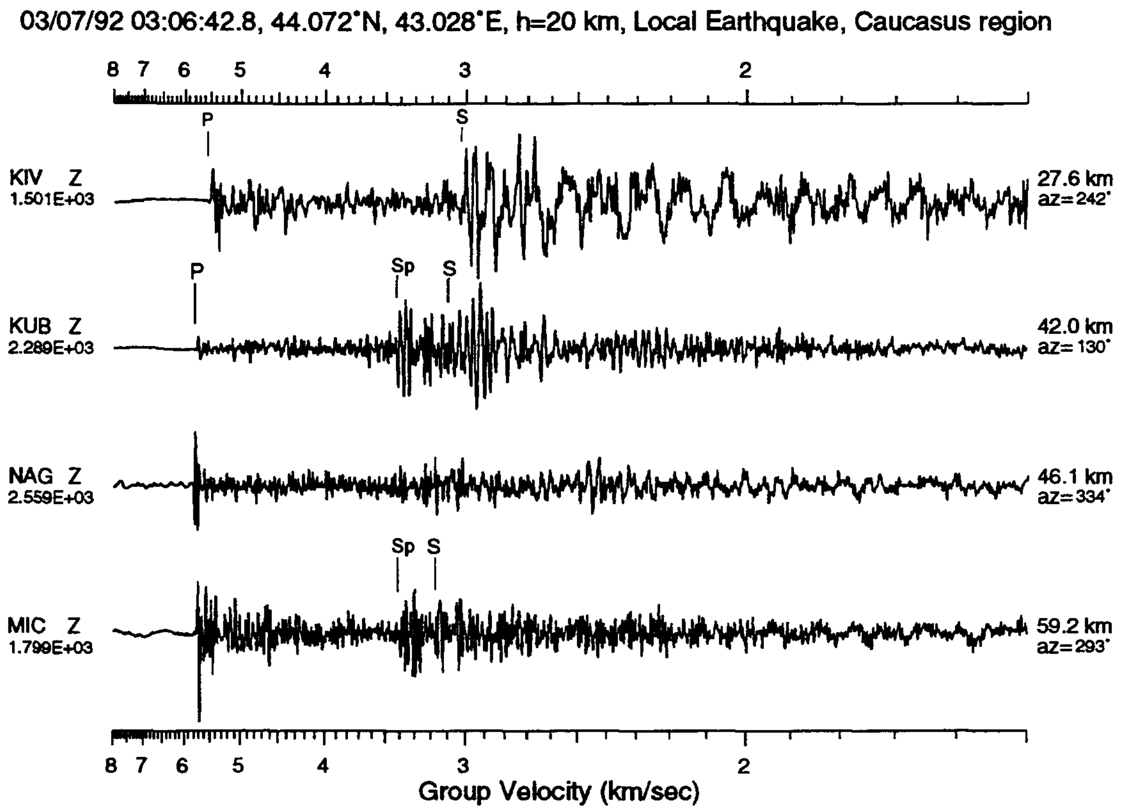

Fig. 2. A group velocity record section of typical vertical-component seismograms from a small local earthquake recorded at the Caucasus Network. Notice strong *P* to *S* converted phases (*Sp*) at stations KUB and MIC.

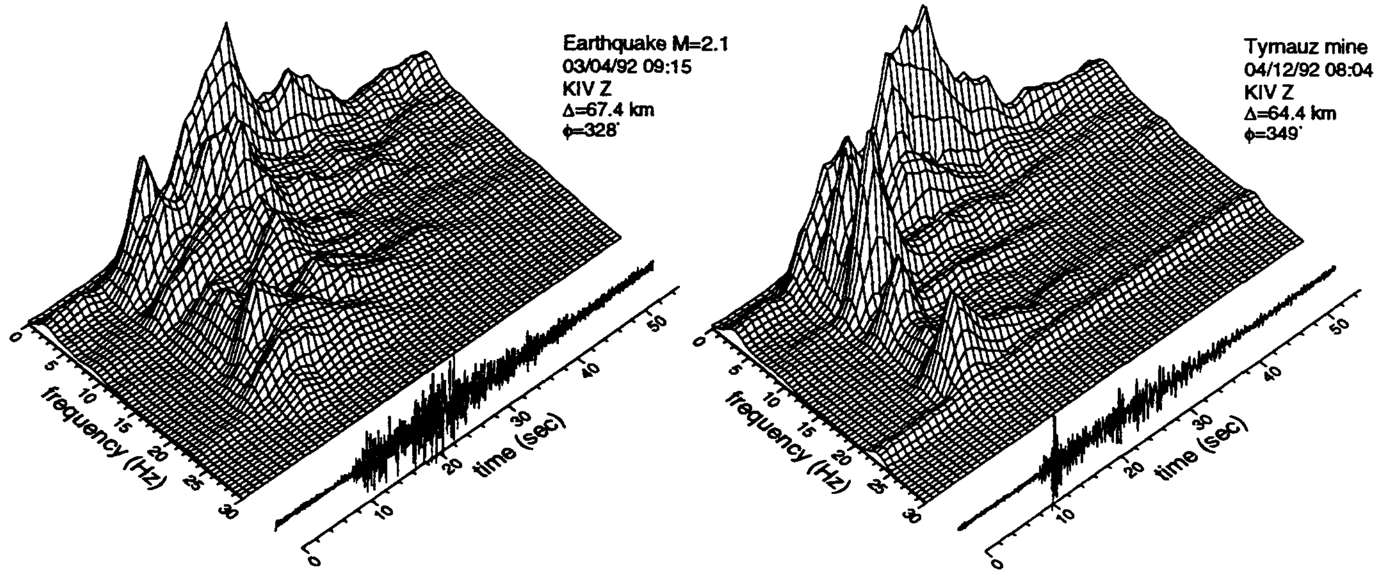

Fig. 3. A comparison of regional seismic signals from an earthquake and a ripple-fired quarry blast. Spectrogram of the earthquake record (*upper panel*) shows random distribution of seismic wave energy, while the spectrogram of the quarry blast record (*lower panel*) shows clear spectral banding due to source multiplicity (ripple-firing). Note that a spectral band at about 22 Hz is due to noise signal, since it appears even before the first arrival *P* wave.

Our observations of high-frequency (1-25 Hz) regional signals from earthquakes and explosions in the southern Russia may be summarized as: 1) *P* waves from the explosions have higher frequency content than *S* waves, while *S* waves from the earthquakes have comparable frequency content as *P* waves (see Fig. 3); 2) *P* and *S* waves from known quarry blasts show frequency banding due to spectral modulation from source multiplicity; 3) records from explosions often show a strong *Rg* phase out to about 100 km.

These examples indicate that high-frequency seismograms show distinctively different patterns in the spectral content of the *P* and *S* signals between earthquakes and explosions. Such high-frequency seismograms suggest that the *Pg/Lg* spectral amplitude ratio can be made the basis of a useful discriminant. The overall differences in frequency content of the *P* and *S* waves from different source types are the basis of our *Pg/Lg* spectral amplitude ratio discriminant.

We report our measurements of the *Pg/Lg* spectral amplitude ratio, using high-frequency, vertical-component digital seismograms from earthquakes and chemical explosions recorded by the Caucasus Network and we evaluate its discrimination capability.

Data

We first present the analysis of digital seismograms from 21 explosions (presumably quarry blasts) and 21 earthquakes to obtain a specific discriminant, which later is applied to other events. Most of the earthquakes are in the magnitude range 1 to 4 and are reported by the Joint Seismic Program Center (JSPC) and the U.S. Geological Survey (PDE). Events are selected to sample a wide range of propagation paths around the network. All quarry blasts are from three known quarry sites plus a previously unknown site identified in this study by calculating spectrograms. Locations of mines and quarries in the region are depicted in Figure 1.

Only explosions for which we had information about the blast characteristics (usually blast time and location) or the blasts whose signals were clearly identified as quarry blast are included. Blast time is one of the most practical discriminant for large chemical explosions. About 87% of events, 71 out of 82 events, located near the Tyrnauz mine are clustered at two peak times (10 am & 4 pm local time) while all events located near the Ust-Djeguta quarry are clustered at 2 pm local time. Distance ranges of the data are 5 to 200 km with means of 120 km and 100 km for earthquakes and explosions, respectively.

Pg and *Lg* signals are windowed with a Gaussian weighting function centered at group velocities around 5.6 km/s and 3.2 km/s, respectively (see Fig. 2). Digital seismograms from the Caucasus Network are sampled at 60 samples/sec and instrument responses of the stations are nearly flat to ground velocity in the frequency band 0.2 to 24 Hz (-3 db level). The *Pg* and *Lg* signals, weighted by the Gaussian functions, are fast Fourier transformed. The resulting amplitude spectra are smoothed with another Gaussian function having $\sigma = 1$ Hz and are re-sampled at every 2 Hz interval from 2 to 24 Hz. Noise analyses indicate that the signal-to-noise (S/N) ratios are quite high in most of the records, but in some cases the signals fall to the background noise level above about 20 Hz. The S/N ratio becomes less than 2 at about 15 Hz for records from distant events ($\Delta > 150$ km). The $\log_{10}(Pg/Lg)$ spectral ratios at discrete frequency points are obtained for each record. Network averaged $\log_{10}(Pg/Lg)$ ratios are then obtained for each event by averaging the discrete frequency values from all stations. Earthquake and explosion populations are well separated in the frequency band 10 to 24 Hz. At frequencies lower than 10 Hz, there is some overlap. Thus, the frequency band 2 – 20 Hz is used in discrimination analysis.

Applications of Discriminant Analysis

To test the discriminant power of the high-frequency *Pg/Lg* spectral ratio, we performed multivariate discriminant analysis on $\log_{10}(Pg/Lg)$ spectral ratios for the data set of earthquakes and explosions. Each training group of 21 events (i.e. 21 explosions, 21 earthquakes) is described by a matrix of 6 rows [($\log_{10}(Pg/Lg)$ at 2 Hz frequency intervals from 10 to 20 Hz] and 21 columns. Details of the linear discriminant function is given for example, Seber (1984) and Kim et al. (1993).

High-frequency network averaged Pg/Lg ratio: The sample data sets consisting of 21 earthquakes and 21 explosions were analyzed using the linear discriminant function. For each event, network averaged $\log_{10}$ (*Pg/Lg*) ratios at frequencies of 10, 12, 14, 16, 18 and 20 Hz correspond to the variables r_1, r_2, r_3, r_4, r_5 and r_6. The linear discriminant function obtained is

$$D(\mathbf{r}) = 5.608 + 1.459\, r_1 - 5.140 r_2 - 5.123 r_3 - 0.217 r_4 + 11.773 r_5 - 20.432 r_6$$

and the Mahalanobis D-squared measure is $\Delta^2 = 8.640$. Assuming equal prior probabilities for the two groups, we assign event $\mathbf{r}$ to the earthquake class if $D(\mathbf{r}) > 0$. Applying this rule to the earthquake and explosion data, we find that all events are classified correctly and the misclassification probability is 0.071. Values of $D(\mathbf{r})$ may be called the discriminant score and are plotted in Fig. 4 with respect to the mean $\log_{10}$ (*Pg/Lg*) spectral amplitude ratio of each event. Vertical lines in the figure denoted as Eq and Ex are the projection of the multivariate mean of the earthquake and explosion populations, respectively. The vertical line, D_0, is the line $D(\mathbf{r}) = 0$, which serves to classify the events when the *a priori* probability of the two populations is the same. The distance between Eq and Ex is the Mahalanobis D-squared measure of distance between two populations. It is shown in Figure 4 that all the earthquake records from various paths in the Northern Caucasus, southern Russia have a mean *Pg/Lg* spectral ratio of about 1, while the explosion records show a mean of about 3. The F statistic for this analysis indicates that there is a statistically significant difference in *Pg/Lg* spectral ratios of signals from the two groups of events.

Discussion and Conclusions

We find that *Pg* waves from explosions have stronger high frequency content than *Lg* waves over the broad high-frequency band 10 – 20 Hz at regional distances in southern Russia near Kislovodsk: the mean ratio for 64 explosion records is about 3. The opposite is true for signals from earthquakes with magnitudes 1–4: the mean *Pg/Lg* ratio for 69 earthquake records in the frequency band 10–20 Hz is about 1. These mean *Pg/Lg* ratios are much higher than the ratios observed in the eastern U. S., where the ratios are 0.5 and 1.25 for the earthquakes and explosions, respectively (Kim et al., 1993). The observed high *Pg/Lg* ratios may suggest stronger attenuation of *S* waves in southern Russia than in the eastern U. S. Very low near surface *S* wave velocity may channel *SV* waves from vertical component into radial component.

The *Pg/Lg* spectral amplitude ratio in the frequency band 10–20 Hz provides discrimination power with a total misclassification probability of about 7%. In a lower frequency band, 2-10 Hz, *Pg/Lg* ratios show poor results and the separation between explosions and earthquakes is less

clear. The *Pg/Lg* ratio is robust as a discriminant to the extent that there is cancellation of spectral reinforcement due to source multiplicity as well as other characteristics, such as event size, corner frequency, some effects of focal depth, and instrument response.

We have shown that the *Pg/Lg* ratio is an adequate discriminant for explosions from earthquakes (magnitude smaller than 4.5) in the southern Russia. The stability of the *Pg/Lg* ratio in discriminating ripple-fired explosions from small regional earthquakes is significant for seismic monitoring in southern Russia. Our results demonstrate the importance of data at frequencies up to at least 20 Hz.

One basis for the empirical success of our proposed high-frequency *Pg/Lg* ratio method is that, if selected spectral amplitude reinforcement occurs at the source (as is the case for ripple-fired blasts), it will affect both early *P* phases as well as later-arriving *Lg* phases. Such spectral scalloping will largely cancel in the ratio we have used. The ratio is robust as a discriminant

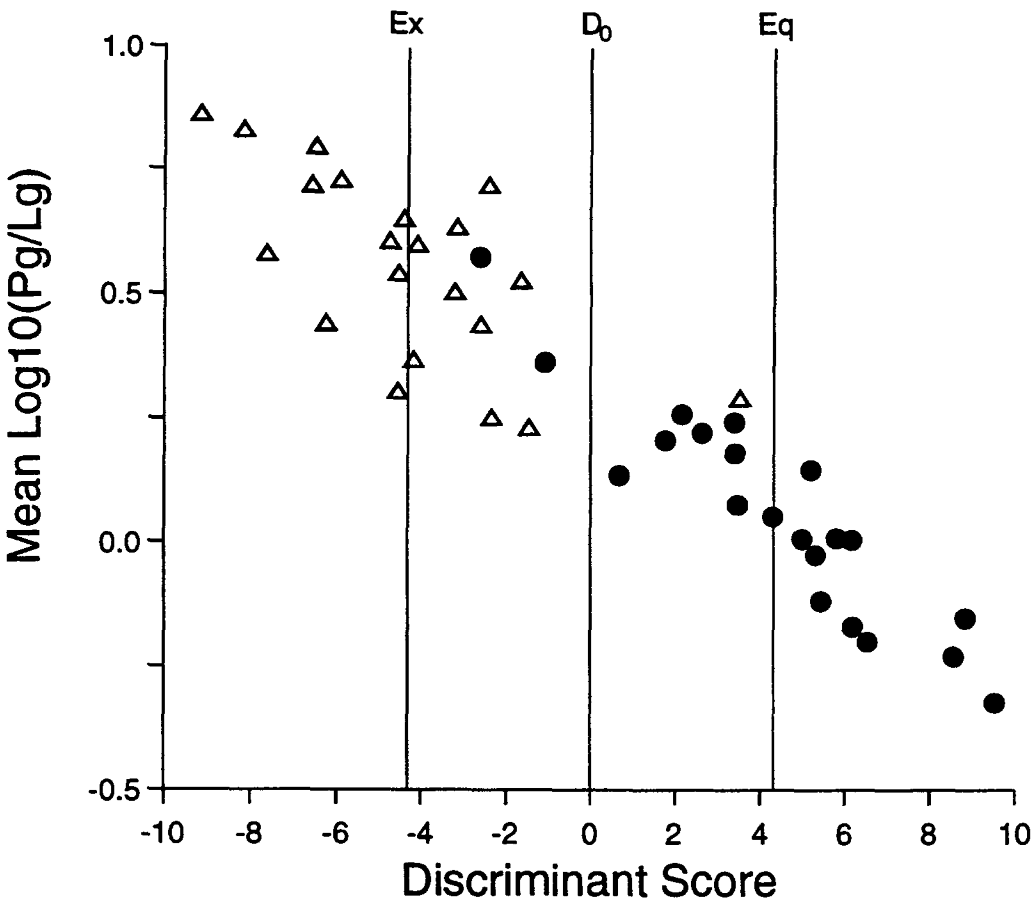

Fig. 4. Discriminant scores of earthquakes (*shaded circles*) and explosions (*triangles*) of the sample data are plotted with their mean network averaged $\log_{10}(Pg/Lg)$ ratios. Note that two populations are also separated by mean $\log_{10}(Pg/Lg)$ ratio ≈ 0.25. Vertical lines denoted as **Ex** and **Eq** are the projection of the multivariate mean of the earthquake and explosion population, respectively. The vertical line $\mathbf{D_0}$ is the classification line. Two earthquakes and an explosion are incorrectly classified and the total misclassification probability is 7.1 %.

to the extent that there is cancellation of other characteristics, such as event size, corner frequency, some effects of focal depth, and instrument response.

We have used only vertical-component seismograms for the discrimination analysis, however inclusion of horizontal components records may improve discrimination power of regional high-frequency records. We observed that *Pg/Lg* ratio of many earthquake horizontal component records show stronger contrast than vertical components. We are working on to include both horizontal component records into discrimination analysis.

It has been reported by some researchers (R. Blandford, person. comm., April, 1994) that correction of anelastic attenuation for both the *P* and *S* signals may enhance the discriminant power of *Pg/Lg* ratio discriminant. However, we believe that it is extremely difficult to correct the signals for attenuation with confidence, at least for the regions with poorly known seismicity.

RECOMMENDATIONS AND FUTURE PLANS

Removal of free surface effect on regional records

Although, high-frequency regional signals on vertical-component show reasonable discrimination power for classifying earthquakes from explosions, use of 3-component records has great potential to discriminate different types of source. Recently, Kennett (1991) showed that interpretation of the regional signals on 3-component records can be facilitated by removing free surface interaction of the incoming wavefield. Kennett (1991) demonstrated that a set of approximate free surface correction operators can be formed to remove the free surface effects over the slowness bands for the main regional phases (see also Aki and Richards, page 190).

An example 3-component records from an underground nuclear explosion recorded at Borovoye (BRVK), Kazakhstan are shown in Figure 5. The rotated seismograms (Z, R, T) show that the *P* waves on Z and R components as well as *Lg* waves on T-component have nearly identical peak amplitude (Fig. 5). However, when the free surface effects are removed from the rotated seismograms by successively applying free surface correction operators appropriate for major regional phases, *P*, *Sn* and *Lg*, the recovered incident wavevector estimates allow us to make direct comparison between the *P*-, *SV*- and *SH*-wave amplitudes along the trace.

The composite incident wavevector traces shows that the *P* waves are mainly on *P*-wavevector component, while *S* waves (*Sn* and *Lg*) are dominantly on *SV*-wavevector component (Fig. 5), hence the amplitudes of major crustal phases reveal clearer radiation characteristics from the source. In particular, the amplitude ratio of *SV* to *SH* in the regional *S* waves clearly indicates the signal being generated by an explosion source.

A very useful result of the free surface correction is that we can make direct comparison between the *P*-, *SV*- and *SH*-wave amplitude in a particular group velocity window and so get closer to the radiation characteristics from the source. This is of potential significance for discriminating different types of sources.

We are working to form a set of simple free surface correction operators suitable for regional signals in the Caucasus region and to evaluate *P/Lg* spectral ratios and other potential discriminants using three component regional records.

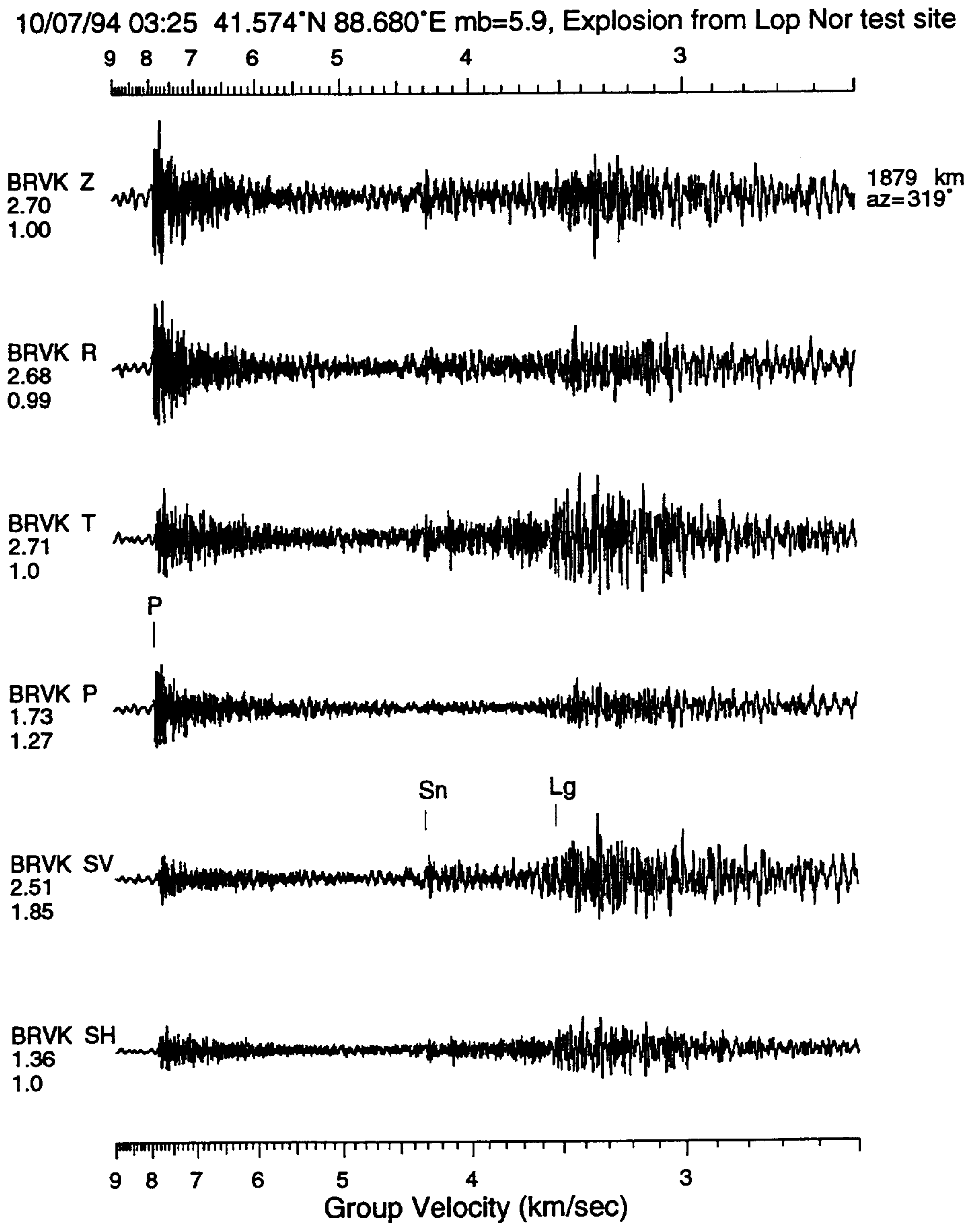

Figure 5. (*Upper three traces*) Rotated 3-component records from an explosion in Lop Nor test site (Z, R and T). The *S* waves are dominantly on T-component, while *P* waves are on Z- and R-component; (*Lower three traces*) Composite incident wavevector component traces (*P*, *SV* and *SH*) produced by applying free surface correction operators successively along the trace. Note that radiation characteristics of the source are more clearly depicted on the decomposed incident wavevector components. Amplitude ratios, Z/T, R/T and P/SH, SV/SH are indicated.

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References

Aki, K. and P. G. Richards (1980). *Quantitative Seismology: Theory and methods*, vol. 1, W. H. Freeman and Co., 1980.

Bennett, T. J. and J. R. Murphy (1986). Analysis of seismic discrimination capabilities using regional data from western United States events, *Bull. Seism. Soc. Am.*, **76**, 1069-1086.

Chael, E. P. (1988). Spectral discrimination of NTS explosions and earthquakes in the southwestern United States using high-frequency regional data, *Geophys. Res.Lett.*, **15**, 625-628.

Davis, J. C. (1986). *Statistics and Data Analysis in Geology*, 2nd ed., John Wiley & Sons, Inc., New York, 646pp.

Evernden, J. F., C. B. Archambeau and E. Cranswick (1986). An evaluation of seismic decoupling and underground nuclear test monitoring using high-frequency seismic data, *Review Geophys., 24*, 143-215.

Kennett, B. L. N. (1991). The removal of free surface interactions from three-component seismograms, *Geophys. J. Int.*, **104**, 153-163.

Kim, W. Y., D. W. Simpson and P. G. Richards (1993). Discrimination of regional earthquakes and explosions in eastern United States using high-frequency data, *Geophys. Res. Lett.*, **20**, 1507-1510.

Murphy, J. R. and T. J. Bennett (1982). A discrimination analysis of short-period regional data at Tonto Forest Observatory, *Bull. Seism. Soc. Am.*, **72**, 1351-1366.

Pomeroy, P. W., W. J. Best, and T. V. McEvilly (1982). Test ban treaty verification with regional data – A review, *Bull. Seism. Soc. Am.*, **72**, S89-S129.

Seber, G. A. F. (1984). *Multivariate Observations*, John Wiley & Sons, Inc., New York, 686pp.

Taylor, S. R., N. W. Sherman and M. D. Denny (1988). Spectral discrimination between NTS explosions and western United States earthquakes at regional distances, *Bull. Seism. Soc. Am.*, **78**, 1563-1579.

Taylor, S. R., M. D. Denny, E. S. Vergino and R. E. Glaser (1989). Regional discrimination between NTS explosions and western U.S. earthquakes, *Bull. Seism. Soc. Am.*, **79**, 1142-1176.